NASA Satellite Monitoring of Water Clarity in Mobile Bay for Nutrient Criteria Development

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Abstract- **Water clarity controls the loss of sunlight reaching the underwater habitats. Because many organisms living in estuarine and coastal waters rely on photosynthesis, water clarity needs to be incorporated into protective water quality standards for these valued ecosystems. To develop the protective standards, a better understanding of causes and effects of water clarity variability at local and regional scales is needed. To that end, NASA remote sensing data are being used to monitor water clarity (measured by light attenuation) and the constituents that decrease water clarity (chlorophyll *a*, total suspended solids, and colored dissolved organic matter) in the estuarine and coastal systems of the northern Gulf of Mexico. The NASA measurements are intended to augment and extend temporal and spatial coverage of water clarity monitoring conducted by the Federal and State environmental agencies in the same areas. The main objective is to develop a methodology for and to demonstrate the feasibility of producing long-term (1984 to present) time series of the water clarity parameters based on combined satellite measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments deployed on the Aqua and Terra spacecraft and from the Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) instruments from the Landsat 4/5 and Landsat 7 spacecraft, respectively. Aqua and Terra MODIS provide daily coverage dating from 2000, while Landsat TM/ETM+ data extend back to 1984, although with frequency of only once per 8 to 16 days. NASA Earth science research results that improved instrument calibration and data processing techniques have enabled merging the time series of observations from Landsat and MODIS. Algorithms for the retrieval of water clarity parameters from satellite data selected for this project are based on the inherent optical properties of water: absorption and scattering of light. The algorithms are refined based on comparison with field data collected during water quality monitoring in Mobile Bay, Alabama. Results of this project will support future interagency collaborative efforts to develop numeric nutrient criteria for estuarine and coastal waters in the Gulf of Mexico and will contribute to addressing the Gulf of Mexico Alliance priority issue of reducing nutrient inputs to coastal ecosystems.**

I. INTRODUCTION

The Clean Water Act is a federal law that regulates surface water quality protection in the United States. All States are obligated to develop and implement, with guidance and oversight from the Environmental Protection Agency, water quality standards to protect the resources of the U.S. waterways [1]. Water quality standards include designated uses— the services that a water body provides (e.g., drinking water, aquatic life, harvestable species, recreation)—and criteria that define the environmental conditions that must be maintained to support the uses. Presently, for estuaries and coastal waters in the Gulf of Mexico, there are no numeric (quantitative) criteria to protect designated uses from effects of nutrients. For most water bodies, this is largely due to the absence of adequate data that would quantitatively link biological conditions to nutrient concentrations. Development of the numeric nutrient criteria has been identified by the Gulf of Mexico Alliance, an organization that fosters collaboration between the Gulf States and U.S. Federal agencies, as a major step leading to reduction in nutrient inputs to coastal ecosystems.

Nutrient enrichment in estuaries and coastal waters can be quantified based on response variables that measure phytoplankton biomass and water clarity. Amount of phytoplankton is usually indicated by chlorophyll *a* concentration. Water clarity is often measured in various ways (e.g., as Secchi disk depth or turbidity), but it can also be precisely defined as light attenuation due to absorption and scattering by water and its suspended or dissolved constituents: chlorophyll *a* (in phytoplankton); total suspended solids (TSS), including suspended sediments and phytoplankton; and colored dissolved organic matter (CDOM). Loss of water clarity can often be associated with increasing chlorophyll *a* concentrations induced by excess nutrients (either directly or through increased CDOM loading due to chlorophyll *a* degradation products). It can also be attributed to increasing TSS concentrations due to elevated landscape erosion and enhancement of sediment resuspension or to increasing human-enhanced CDOM loading associated with paper and pulp mills as well as with hydrologic modifications, such as drainage of canals and wetlands.

Long-term, spatially and temporally resolved measurements of chlorophyll *a* concentration, TSS concentration, and water clarity are needed to establish reference conditions and to quantify stressor-response relationships (two possible approaches to nutrient criteria development). However, measurements at appropriate scales and resolution are often impossible to obtain cost-effectively via such methods as in situ sampling from boats and mooring stations. This project uses time series of NASA Earth observations acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments deployed on the Aqua and

Terra spacecraft and by the Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) instruments from the Landsat 4/5 and Landsat 7 spacecraft, respectively. These time series augment and extend temporal and spatial coverage of water clarity monitoring conducted by the U.S. Federal and State environmental agencies in the Gulf of Mexico coastal waters and estuaries.

Since 2000, MODIS instruments have been providing near-daily remote sensing measurements that have several advantages over those acquired by the previous generations of similar instruments. Among these advantages are a larger number of spectral bands, finer spatial resolution, and more reliable radiometric calibration [2]. Long-term stability of MODIS characteristics has been especially important in enabling creation and analysis of multiyear time series of atmospheric, terrestrial, and ocean data products [3,4]. Ocean color data products have been successfully generated from MODIS measurements acquired over open oceans [5], and in recent years, significant efforts have been made to increase confidence in ocean color products derived for coastal regions [6,7].

Landsat TM and ETM+ instruments have provided Earth imagery from 1982/84 through the present. Many studies have been carried out to retrieve from Landsat images such water quality measures as concentrations of suspended sediments and chlorophyll. In recent years, significant efforts have been made to cross-calibrate the Landsat sensors and assess their temporal stability [8]. These efforts enabled creation of long-term time series of Landsat data and their application in several areas [9]. With improved atmospheric correction methods, it becomes possible to merge time series of observations from Landsat and MODIS [10]. This project's work on merging the Landsat and MODIS time series is in progress and its results will be reported in the future.

II. METHODS

MODIS time series of water clarity parameters were created from the Level 1B MODIS data products obtained from the MODIS Adaptive Data Processing System / Level 1 and Atmosphere Archive and Distribution System (MODAPS/LAADS).[1] MODIS data acquired by the instruments from both the Terra and Aqua satellites were used in this project. The Level 1B calibrated radiance products MOD02 and MYD02, and the accompanying geolocation products MOD03 and MYD03, were processed using the SeaDAS software (version 5.3) to apply atmospheric correction and to retrieve inherent optical properties (IOPs) of coastal ocean and estuarine waters.[2] Atmospheric correction was based on the recently developed method that uses short-wave infrared bands, instead of near infrared bands, to compensate for effects of atmospheric aerosols over turbid waters in coastal regions [6]. The IOPs were calculated using the quasi-analytical algorithm of Lee et al. [11]. The IOPs used to produce water clarity parameters included

- total absorption coefficient at 488 nm, $a(488)$,
- total backscattering coefficients at 488 nm and 555 nm, $b_b(488)$ and $b_b(555)$,
- phytoplankton absorption coefficient at 443 nm, $a_{ph}(443)$, and
- gelbstoff + detritus absorption coefficient at 412 nm, $a_{dg}(412)$.

The IOPs were calculated with nominal ground sample distance (GSD) of 250 m (at nadir). Bilinear interpolation was used in SeaDAS software when MODIS band data required in processing had a larger GSD (500 m or 1 km). Based on SeaDAS quality flags generated for each pixel, water clarity parameters were not produced for pixels that were identified as (1) land, (2) cloud and/or ice, (3) affected by severe sun glint, and (4) acquired at high satellite zenith angle.

Diffuse attenuation coefficient for the photosynthetically active radiation (PAR), $K_d(PAR)$, is the main water clarity parameter used in this study. $K_d(PAR)$ at the depth of z meters is estimated from the IOPs using the following equations (with data from the MODIS band at 488 nm substituted for the required 490-nm data) [12]

$$K_d(PAR, z) = K_1 + \frac{K_2}{\sqrt{1+z}}, \text{ with} \tag{1}$$

$$K_1 = \left[\chi_0 + \chi_1\sqrt{a(490)} + \chi_2 b_b(490)\right](1 + \alpha_0 \sin\theta_a), \text{ and} \tag{2}$$

$$K_2 = [\zeta_0 + \zeta_1 a(490) + \zeta_2 b_b(490)](\alpha_1 + \alpha_2 \cos\theta_a). \tag{3}$$

A separate value of the satellite viewing angle θ_a was used for each pixel (as provided in the MODIS datasets). Values of the model parameters used in the calculations of $K_d(PAR)$ are [13]

$\chi_0 = -0.057 \text{ m}^{-1}$	$\chi_1 = 0.482$	$\chi_2 = 4.221$	$\alpha_0 = 0.090$	
$\zeta_0 = 0.183 \text{ m}^{-1}$	$\zeta_1 = 0.702$	$\zeta_2 = -2.567$	$\alpha_1 = 1.465$	$\alpha_2 = -0.667$

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[1] http://ladsweb.nascom.nasa.gov/
[2] http://oceancolor.gsfc.nasa.gov/seadas/

Predicted diffuse attenuation coefficients are bounded by $K_d(\text{PAR}, 0) = K_1 + K_2$ and $K_d(\text{PAR}, \infty) = K_1$, and these two quantities are used in this study to characterize water clarity.

Total suspended solids are the main constituent affecting water clarity. *TSS* concentration was calculated from the following empirical equation derived by Gould et al. from measurements in Mobile Bay [14]

$$TSS = 1.58153 \frac{\text{g}}{\text{m}^2} \cdot b(555) \tag{4}$$

Total scattering coefficient was calculated from backscattering coefficient using the formula $b(555) = 50\, b_b(555)$ or $b_b(555) = 0.02\, b(555)$ that uses the value of the b_b/b ratio similar to the one reported previously [15]: $b_b = 0.01829 \cdot b + 0.00006\ \text{m}^{-1}$. Other values of the b_b/b ratio have been reported; for example [16]: $b_b(555) = 0.00926 \cdot b(555)$ and $b_b(555) = 0.01370 \cdot b(555)$. Therefore, the proportionality factor of 100 was used in this study in addition to the one equal to 50.

Chlorophyll *a* concentration (*Chl*, in mg·m^{-3}) was calculated from the phytoplankton absorption coefficient using the following equation with the appropriate model constants [17]

$$Chl = \left[\frac{a_{\text{ph}}(443)}{A(443)} \right]^{\frac{1}{1-B(443)}} \text{ with } A(443) = 0.0394\ \text{m}^{-1} \text{ and } B(443) = 0.3435. \tag{5}$$

Data from the MODIS band at 443 nm were used in the current calculations of chlorophyll concentration, but other MODIS bands may also be used in future work to calculate mean value and assess applicability of (5) in Mobile Bay [18].

In the first approximation, light attenuation by CDOM is estimated from the gelbstoff + detritus absorption coefficient at 412 nm, $a_{\text{dg}}(412)$.

Time series of water clarity parameters were extracted from MODIS data products in two ways: for selected point locations and for areas of interest defined by polygons in geographic coordinates. Point series were produced by finding for each day a MODIS pixel that is the closest to the selected location and is situated not farther from it than a distance to an adjacent MODIS pixel in the same scan line. Area-aggregated series were created by averaging for each day all MODIS pixels located within boundaries defined by a polygon (an example of such an area, covering Bon Secour Bay in Mobile Bay, is shown in Fig. 1). In either case, when data were available from both Aqua and Terra satellites, mean values of water clarity parameters were included in the time series.
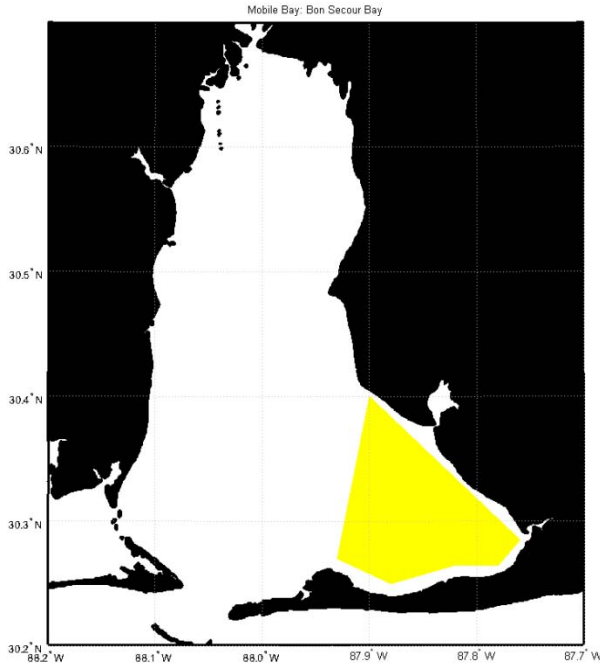

Fig. 1 Bon Secour Bay area (yellow patch) in Mobile Bay selected for aggregation of remote sensing observations to generate time series of water clarity parameters.
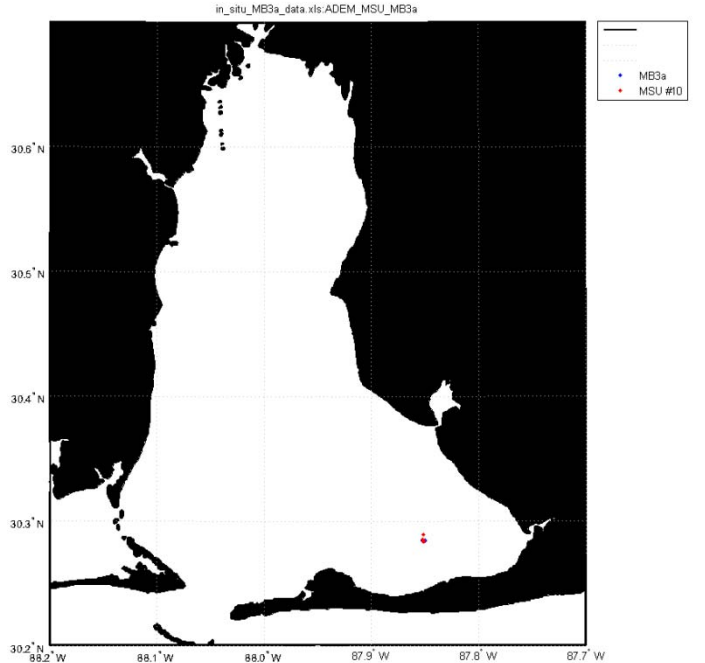

Fig. 2 Locations of water sampling and in situ measurements collected in Bon Secour Bay at ADEM station MB3a (blue dots) and MSU station #10 (red dots)

Point time series were produced for locations of in situ measurement and water sampling stations. Surface water monitoring data were obtained from two sources: Alabama Department of Environmental Management (ADEM) and Mississippi State University (MSU). ADEM data include monthly sampling results from 11 coastal trend stations located in Mobile Bay and vicinity for the time period 2004-2006 [19]. Sampling locations for one of the trend stations, MB3a, are shown in Fig. 2. MSU data originate from both water sample analyses and in situ measurements. The data were acquired monthly in Mobile Bay and in an area located south of the bay during the time period 2007-2008 [20]. MSU station #10 is collocated with the ADEM's MB3a station. Sampling locations for the MSU station #10 are also shown in **Error! Reference source not found.**

III. RESULTS

A. *Comparison of MODIS Water Clarity Time Series with In Situ Data*

Time series of water clarity parameters were generated from MODIS data for several locations in Mobile Bay where surface monitoring has been conducted by ADEM and MSU. Time series extracted for one of these locations, the MB3a monitoring station in Bon Secour Bay, are shown in Fig 3. The data series were generated for nearly 9 years, from the day the first MODIS observations from the Terra satellite became available in early 2000 until the end of 2008. Although MODIS data are acquired daily (or even twice per day starting in 2002 when the second MODIS instrument was launched on the Aqua satellite), frequent cloud cover and limits of satellite viewing geometry restricted generation of time series to only about 100 data points per year. This number of water clarity measurements is still much larger than the typical monthly sampling traditionally performed from boats.
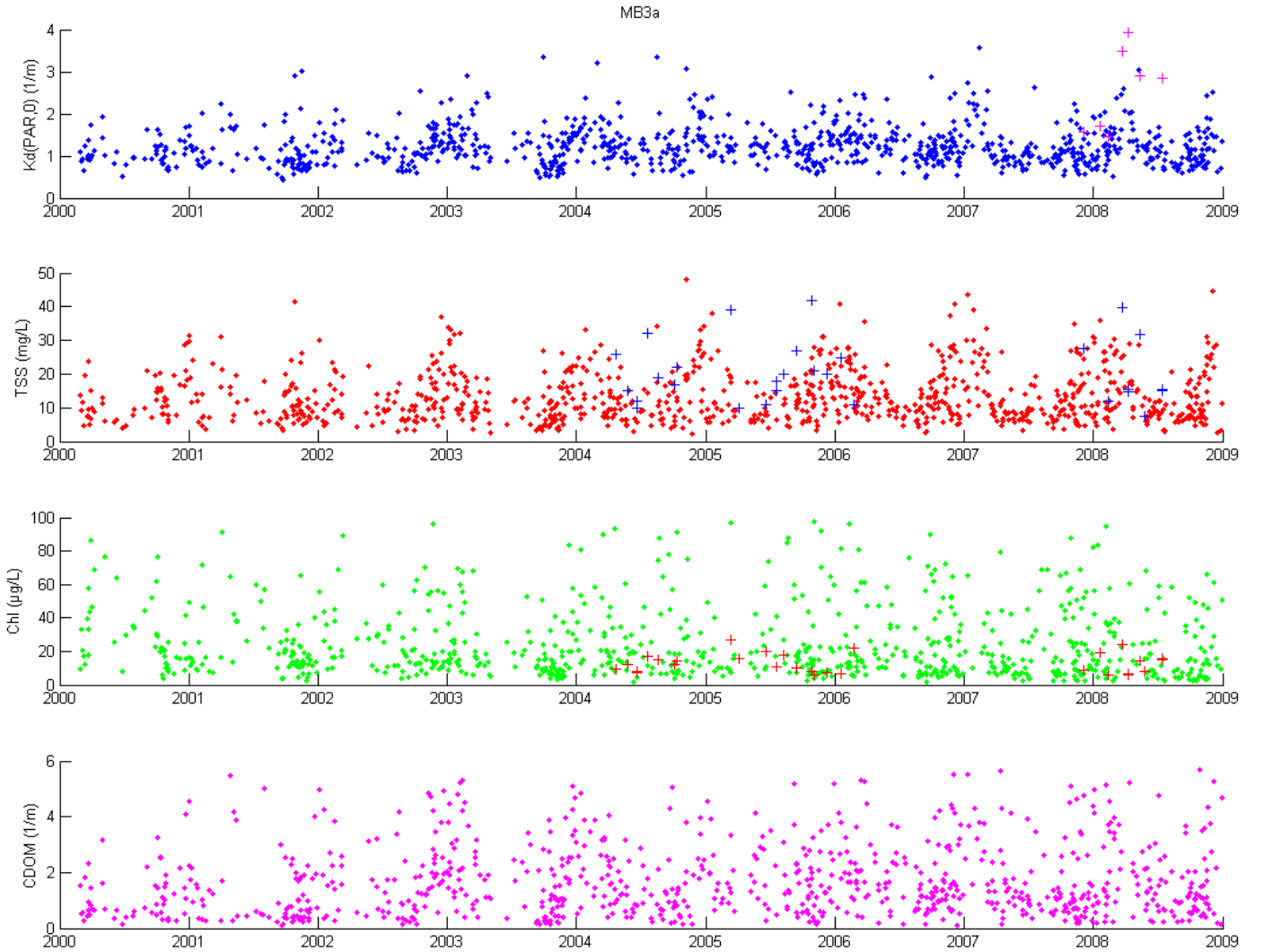

Fig 3 Time series of water clarity parameters (PAR diffuse attenuation coefficient, total concentration of suspended solids, chlorophyll *a* concentration, and absorption coefficient for CDOM) retrieved from MODIS remote sensing measurements (dots) and compared with water sampling and in situ measurements (crosses) collected in Mobile Bay at the MB3a station by ADEM (2004-2006) and MSU (2007-2008).

Most noticeable in Fig 3 is the short-term variability of the observables. Very often water clarity parameters change dramatically from day to day. Similar variability is visible in the ADEM/MSU water sampling and in situ measurements data shown in the figure. Nevertheless, seasonal trends are also visible in the remote sensing observations, especially in TSS concentration. TSS concentration, retrieved using (4) with $b/b_b = 100$, displays the best agreement with the in situ data. When $b/b_b = 50$ is used in (4), the comparison with the in situ data shows that values retrieved from MODIS measurements underestimate TSS concentrations observed in Mobile Bay (see Fig. 4). For $K_d(PAR,0)$, comparison with the in situ measurements shown in Fig 3 is only partially satisfactory, but for several other sampling stations (not shown here), results of such comparisons are much better. Chlorophyll *a* concentrations retrieved from MODIS data using (5) often agree quite well with in situ measurements, but occasionally algorithm (5) severely overestimates the *Chl* concentrations observed in Mobile Bay.

B. *MODIS Water Clarity Time Series Aggregated over an Area*

In comparison with the MODIS time series retrieved for selected point locations, area-aggregated time series consist of a significantly larger number of data points: Fig. 5 shows that about 200 points have been retrieved per year for the Bon Secour Bay area shown in Fig. 1. The area-aggregated time series also appear to have higher signal-to-noise ratio that enable better distinguishing of seasonal trends in water clarity parameters and identification of such extreme episodes as the TSS concentration during spring 2005. While chlorophyll *a* time series display a broad range of values, rather uncorrelated with time, the CDOM time series, which also include detritus, reveal seasonal changes. Water clarity (light attenuation) varies by a factor of two between the winter and summer months. However, based on Fig. 5, no significant long-term (multi-year) trend in water clarity parameters in Bon Secour Bay is apparent between years 2000 and 2008. Time series of water clarity parameters derived in this project for other parts of Mobile Bay show similar absence of long-term changes during the time period covered by the MODIS satellite sensors.
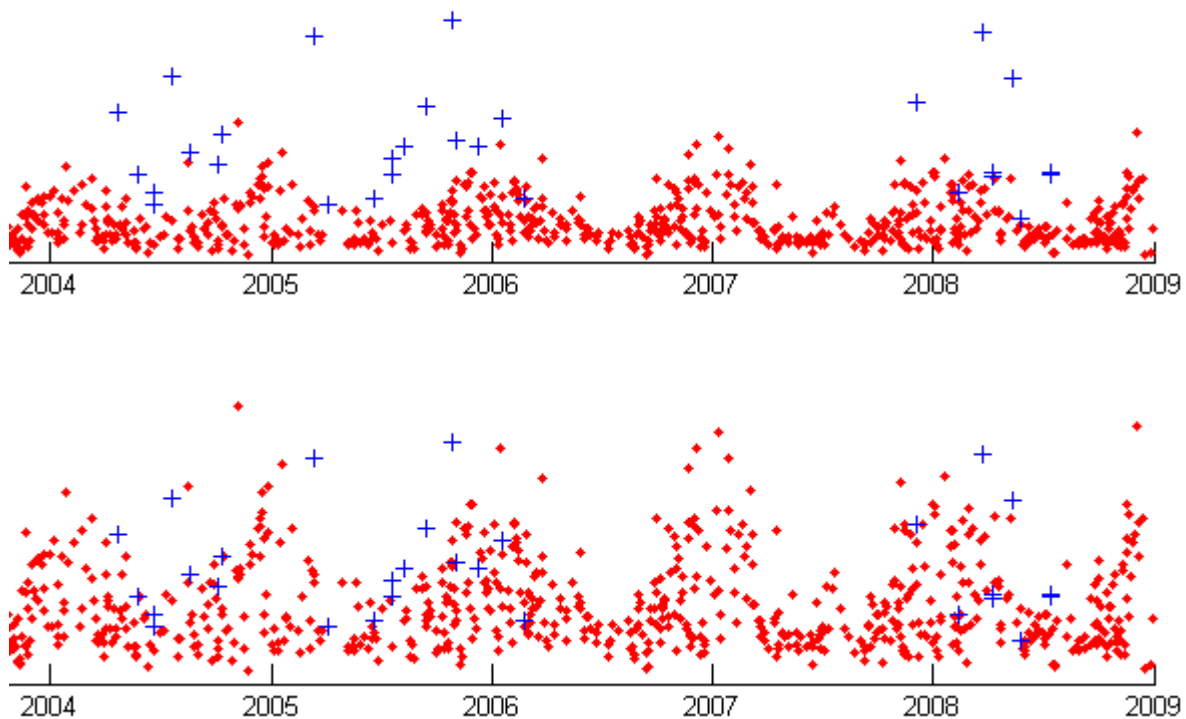

Fig. 4. Comparison between subsets of TSS time series generated from MODIS data (dots) using (4) with $b/b_b = 50$ (top) and $b/b_b = 100$ (bottom) and the surface water monitoring measurements (crosses) collected by ADEM (2004-2006) and MSU (2007-2008) at the MB3a sampling station. TSS scale and units are the same as in Fig 3.
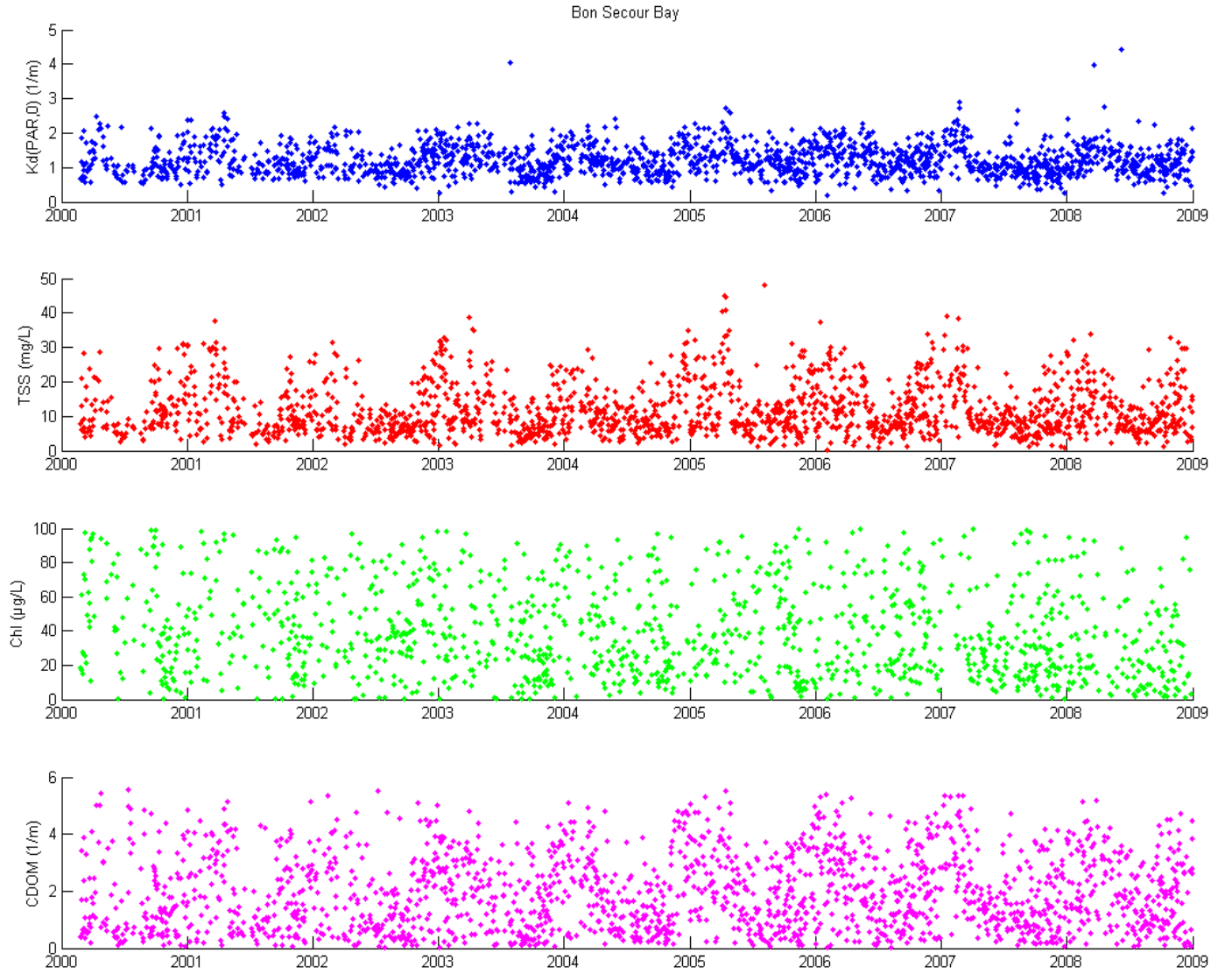
Fig. 5 Time series of water clarity parameters retrieved from MODIS remote sensing measurements for the Bon Secour Bay area.

IV. DISCUSSION

This project has demonstrated that it is feasible to derive from MODIS daily measurements time series of water clarity parameters that will provide coverage of a specific location or an area of interest for 30-50% of days. The time series derived for estuarine and coastal waters display much higher variability than time series of ecological of parameters (such as vegetation indices) derived for land areas. Thus, temporal filtering often applied in terrestrial studies cannot be used effectively in ocean color processing. Creating temporal averages (e.g., monthly or annual), although often employed and worthy of testing, may not be very effective either in tracking trends or responses. The short-term variability of the coastal ocean color time series also emphasizes the need for more frequent (even hourly) observations, such as those from the coastal waters imager that was originally planned for the GOES-R geostationary satellite.

IOP-based algorithms for retrieval of diffuse light attenuation coefficient and TSS concentration perform well for the Mobile Bay environment. Only a minor adjustment was needed in the TSS algorithm, despite generally recognized dependence of such algorithms on local conditions. Application of these algorithms for other Gulf of Mexico estuaries should be successful as well. The IOP-based algorithm for retrieval of chlorophyll *a* concentration, (5), has not performed as well. A more reliable *Chl* algorithm is needed that may be based on IOPs at additional wavelengths or on remote sensing reflectance from multiple spectral bands. The CDOM algorithm also needs improvement to provide better separation between effects of CDOM (gelbstoff) and detritus. Identification or development of such algorithm requires more data from in situ measurements of CDOM concentration in Gulf of Mexico coastal waters.

Long-term time series of water clarity parameters are required to establish reference conditions and/or to quantify stressor-response relationships in estuarine and coastal waters. Current, 9-year time series need to be extended into the 1990s and 1980s using data collected by the Landsat satellites. Preliminary work on merging Landsat and MODIS time series conducted under this project provided promising results. The final outcome of those efforts will be reported in the future. The joint Landsat/MODIS time series of water clarity measurements will support development of numeric nutrient criteria for Mobile Bay and other Gulf of Mexico estuaries.

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